

# All-sky component separation for the Planck mission

V. Stolyarov<sup>1,2</sup>, M.P. Hobson<sup>2</sup>, M.A.J. Ashdown<sup>2</sup>, A.N. Lasenby<sup>2</sup>

<sup>1</sup> *Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK*

<sup>2</sup> *Astrophysics Group, Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, UK*

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## ABSTRACT

An harmonic-space maximum-entropy method (MEM) is presented for separating the emission from different physical components in all-sky observations by the forthcoming Planck satellite. The analysis is performed at full Planck resolution, with a pixel size of 1.7 arcmin, which corresponds to  $\ell_{\max} \approx 6000$ . The simulated Planck data include emission from the CMB, the kinetic and thermal Sunyaev-Zel'dovich (SZ) effects from galaxy clusters, as well as Galactic dust, free-free and synchrotron emission. Our simulations also assume homogeneous, uncorrelated pixel noise, although this is not a requirement of the method. We find that the MEM technique produces faithful reconstructions of the main input components over the whole sky, without the need to perform a Galactic cut. The CMB power spectrum is accurately recovered up to  $\ell \approx 2000$ . The algorithm is parallelised so that the entire reconstruction can be performed in  $\sim 6$  hr using 30 R10000 processors on an SGI Origin 2000 supercomputer and requires 14 Gb of RAM.

**Key words:** methods – data analysis – techniques: image processing – cosmic microwave background.

## 1 INTRODUCTION

Two new cosmic microwave background (CMB) satellite missions are currently in preparation. The NASA MAP satellite is expected to be launched in late 2001, followed by the ESA Planck Surveyor in 2007. Both missions will provide detailed all-sky maps at a number of observing frequencies. The main aim of these new satellite projects is to obtain an accurate map of CMB anisotropies over the whole sky and produce a definitive measurement of the CMB power spectrum. This should allow tight constraints to be placed on fundamental cosmological parameters and distinguish between competing theories of structure formation.

The maps produced by these satellites will, however, contain contributions from various foreground components, most notably Galactic dust, free-free and synchrotron emission as well as the kinetic and thermal Sunyaev-Zel'dovich (SZ) effects from galaxy clusters. In addition, significant contamination from extragalactic point sources is also expected. It is therefore clear that in order to obtain maps of the CMB anisotropies alone, it is necessary to separate the emission due to these various components. Traditional methods for performing the separation include singular-valued decomposition and Wiener filtering (Bouchet, Gispert & Puget 1996; Tegmark & Efstathiou 1996), although a recent preliminary application of neural-networks to this problem appears promising (Baccigalupi et al. 2000). A review of tradi-

tional foreground separation techniques is given by Bouchet & Gispert (1999).

In a previous paper (Hobson et al. 1998; hereafter Paper I), a separation was performed on simulated Planck Surveyor observations of a  $10 \times 10$  deg<sup>2</sup> field (see Bouchet et al. 1997; Gispert & Bouchet 1997), using a non-linear Fourier-space maximum-entropy method (MEM) that reduces to traditional Wiener filtering in the absence of non-Gaussian signals. It was found that faithful reconstructions may be produced not only of the CMB anisotropies but also of the Galactic components and the thermal SZ effect from massive clusters. It was also shown that the MEM technique outperformed standard Wiener filtering, particularly in reconstructing highly non-Gaussian components such as the SZ effects. An application of the MEM component separation technique to simulated MAP data of a  $10 \times 10$  deg<sup>2</sup> field was presented by Jones, Hobson & Lasenby (1999).

In Hobson et al. (1999), the basic MEM algorithm was extended to identify and remove contamination from extragalactic point sources, and has been further refined by Vielva et al. (2001) by combining it with a Mexican hat wavelet filtering technique.

A great advantage of forthcoming satellite missions, however, is the prospect of obtaining all-sky maps at each observing frequency, from which one would hope to reconstruct maps of the emission from each physical component over the whole sky simultaneously, rather than just in small patches. Indeed, Prunet et al. (2001) recently presented the

first application of the Wiener filter component separation algorithm to simulated all-sky data from the MAP experiment. Their analysis was performed up to  $\ell_{\max} = 512$  and included contributions from the three dominant astrophysical components expected in the five MAP frequency channels, namely CMB and Galactic dust and synchrotron emission.

It is, however, the Planck mission that provides the greatest challenge for performing a component separation. Planck will map the whole sky in 10 frequency bands from 30 to 857 GHz and at angular resolutions ranging from 33 to 4.5 arcmin. To ensure Nyquist sampling of the sky emission, the basic pixel size for Planck reconstructions is  $\sim 2$  arcmin, which corresponds to  $\sim 50$  million pixels in each all-sky map and maximum multipole  $\ell_{\max} \approx 6000$ . However, the problem is not simply one of computational complexity. Owing to its greater frequency coverage and higher angular resolution, Planck is sensitive to the full range of astrophysical foreground outlined above, and thus provides an opportunity to map each of these components individually. In particular the highly non-Gaussian SZ effects from galaxy clusters are of considerable cosmological interest.

In this paper, we therefore extend the Fourier-space MEM algorithm to perform reconstructions on the whole celestial sphere. Since the algorithm is inherently computationally fast and efficient, and, moreover, can be straightforwardly parallelised to take advantage of existing supercomputing facilities, we are able to perform reconstructions to full Planck resolution. As well as the vastly increased computational burden over the analysis presented in Paper I, when performing all-sky reconstructions we also encounter the problem of highly inhomogeneous emission due to Galaxy. The latter leads to foreground maps with a very large dynamic range. Nevertheless, we show that presence of bright emission from the Galactic plane does not severely affect the accuracy of the reconstructions obtained, and that it is *not* necessary to impose a Galactic cut on the data prior to the component separation analysis. We note, however, that a Galactic cut can still be performed in order to prevent contamination from poorly modelled strong Galactic emission regions.

## 2 MODEL OF THE MICROWAVE SKY

To create simulated Planck observations, we must first build a plausible model of the emission over the whole sky at each Planck frequency. We assume the main contributions to this emission are from the primordial CMB, the kinetic and thermal SZ effects from galaxy clusters, and the Galactic dust, synchrotron and free-free components. In this paper, we will assume that extragalactic point sources may be removed earlier in the analysis using the satellite observations themselves together with existing surveys, or by applying the joint MEM and Mexican hat wavelet technique discussed in Vielva et al. (2001) to the data map at each frequency. The generalisation of this joint scheme to all-sky observations and using all the frequencies simultaneously will be presented in a forthcoming paper.

Following the notation of Paper I, we choose to work in units of equivalent CMB thermodynamic temperature. If  $\Delta I(\mathbf{x})$  is the fluctuation in the specific intensity at some frequency  $\nu$  in the direction  $\mathbf{x}$ , then the corresponding fluctuation in the equivalent CMB thermodynamic temperature

is given by

$$\Delta T(\mathbf{x}, \nu) = \frac{\Delta I(\mathbf{x}, \nu)}{\partial B(\nu, T)/\partial T|_{T=T_0}},$$

where  $B(\nu, T)$  is the Planck function and  $T_0 = 2.726$  K is the temperature of the CMB (Mather et al. 1994). As in paper I, we also assume that the contribution from the  $p$ th physical component can be factorised into a spatial template  $s_p(\hat{\mathbf{x}})$  at reference frequency  $\nu_0$  and a frequency dependence  $f_p(\nu)$ , so that

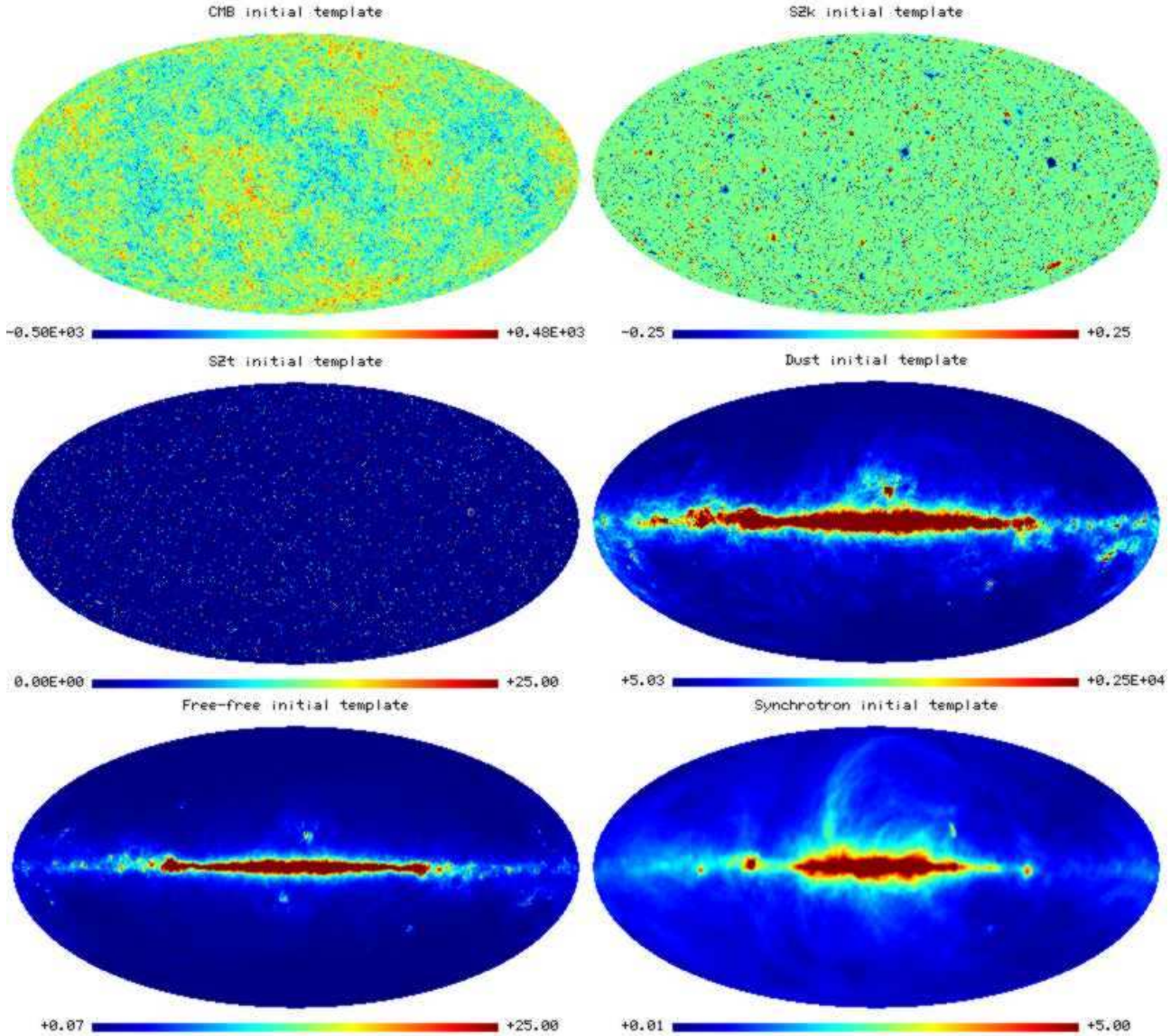
$$\Delta T(\hat{\mathbf{x}}, \nu) = \sum_{p=1}^{n_c} \Delta T_p(\hat{\mathbf{x}}, \nu) = \sum_{p=1}^{n_c} f_p(\nu) s_p(\hat{\mathbf{x}}). \quad (1)$$

We take as our reference frequency  $\nu_0 = 300$  GHz, and normalise the frequency behaviour so that  $f_p(\nu_0) = 1$  for all the physical components.

It is clear that (1) represents the somewhat idealised case in which the spectral index of each physical component does not vary with direction on the sky. While this assumption is valid for the CMB and the two SZ effects, it is unlikely to hold for the Galactic components. This was not a severe concern in Paper I, since the analysis there was restricted to a  $10 \times 10 \text{ deg}^2$  patch of sky over which the spectral indices of the Galactic components might reasonably be expected not to vary significantly (particularly in regions of high Galactic latitude). For an all-sky reconstruction, however, the assumption almost certainly does not hold, even approximately. Nevertheless, as mentioned in Paper I and investigated further in Jones et al. (1999), it is possible for the separation algorithm to accommodate varying spectral indices by including extra components in the reconstruction. For example, if we assume that the frequency dependence of the synchrotron emission is of the form  $I \propto \nu^{-\beta}$ , with  $\beta = -0.7 \pm 0.2$ , we simply include two synchrotron channels, one with  $\beta = -0.5$  and one with  $\beta = -0.9$ , or even with intermediate values, and afterwards sum over these channels to obtain the reconstructed synchrotron map. Alternatively, one can consider deviations from the mean spectrum as just another template to be recovered with a modified spectral behaviour as obtained by linearising the frequency dependence of the intensity with these deviations (Bouchet et al. 1996). We will pursue these ideas in a forthcoming paper, but for now we consider only the idealised situation represented by (1).

Each of the six physical components of emission are simulated in the HEALPIX<sup>1</sup> pixelisation scheme (Gorski, Hivon & Wandelt 1999) with  $N_{\text{side}} = 2048$ , which corresponds to  $\sim 50$  million pixels of size 1.7 arcmin, or  $\ell_{\max} = 3N_{\text{side}} - 1 = 6143$ . Since the highest angular resolution of the Planck satellite is 4.5 arcmin, a pixel size of 1.7 arcmin ensures that the fields are Nyquist sampled. The models used for each physical component are discussed below. These input maps are plotted in Fig. 1 at 300 GHz, and the corresponding power spectra are shown in Fig. 2.

<sup>1</sup> <http://www.eso.org/kgorski/healpix/>



**Figure 1.** All-sky realisations of the six main physical components contributing to the sky emission at Planck wavelengths. The components are primordial CMB, kinetic and thermal SZ effects from clusters and Galactic dust, free-free and synchrotron emission. Each map is defined in the HEALPIX pixelisation scheme with  $N_{\text{side}} = 2048$ , which corresponds to  $\sim 50 \times 10^6$  pixels of size 1.7 arcmin. Each map is plotted at 300 GHz in units of  $\mu\text{K}$ .

## 2.1 CMB anisotropy

The primordial CMB anisotropy field is generated over the whole sky using the SYNFAST routine in the HEALPIX software package, and corresponds a Gaussian realisation of a spatially-flat standard inflationary CDM model with  $\Omega_m = 0.35$ ,  $\Omega_\Lambda = 0.65$ ,  $\Omega_b h^2 = 0.02$  and  $h = 0.65$ , for which the  $C_\ell$  coefficients were created using CMBFAST (Seljak & Zaldarriaga 1996).

## 2.2 Thermal and kinetic SZ effects

The thermal SZ effects from individual clusters were simulated using the gas dynamics code of Eke, Navarro & Frenk (1998), from which 210 cluster templates were obtained.

These templates were distributed on the sky according to a Poisson distribution and with random orientations. The redshift distribution was chosen to be consistent with the Press-Schechter model (Press & Schechter 1974) for a  $\Omega_m = 0.35$ ,  $\Omega_\Lambda = 0.65$  cosmology (R. Kneissl, private communication). To simulate the kinetic SZ effect, the cluster radial velocities are assumed to be Gaussian distributed with a dispersion of  $400 \text{ km s}^{-1}$  at  $z = 0$ .

## 2.3 Galactic dust emission

The Galactic dust contribution is modelled using the DIRBE-IRAS  $100\text{-}\mu\text{m}$  dust map (Schlegel, Finkbeiner & Davis 1998). The angular resolution of the map is around 5

arcmin, which is comparable with Planck resolution in the highest frequency channels. The emission at each Planck frequency can be predicted by extrapolating the 100- $\mu\text{m}$  flux assuming a one-component dust model with a temperature  $T_{\text{dust}} = 18$  K and dust emissivity  $\beta = 2$ . The colour correction factor for the DIRBE 100- $\mu\text{m}$  filter was also taken into account; (see Finkbeiner, Davis & Schlegel 1999).

## 2.4 Galactic synchrotron emission

The basic template of the synchrotron emission is the de-striped version of the 408 MHz Haslam survey (Haslam et al. 1982), to which additional structure was artificially added at sub-degree angular scales by extrapolating the angular power spectrum of the Haslam survey as  $C_\ell \propto \ell^{-3}$ . The synchrotron map at 300 GHz is obtained by extrapolating the 408 MHz survey using an all-sky map of the spectral index constructed by combining the low frequency surveys at 408 MHz, 1420 MHz (Reich & Reich 1986) and 2326 MHz (Jonas, Baart & Nicholson 1998) and padding the unobserved area around the South pole with the mean spectral index, at a resolution (FWHM) of 10 degrees (G. Giardino, private communication). To predict the synchrotron contribution at the Planck observing frequencies, a constant intensity spectral index  $\beta = -0.9$  was assumed.

## 2.5 Galactic free-free emission

Reliable maps of Galactic free-free emission are not currently available, although experiments such as the H $\alpha$  Sky Survey<sup>2</sup> (Gaustad et al. 2001) and the Wisconsin H $\alpha$  Mapper — WHAM<sup>3</sup> (Haffner 2001) should soon provide maps that could be used as templates. The resolution of the surveys is about 0.8 arcmin for H $\alpha$  Sky Survey and about 1 degree for WHAM. For the time being, however, we create a free-free template based on the DIRBE/IRAS dust map, of which 60 per cent of the emission is a dust-correlated component and 40 per cent is uncorrelated. The uncorrelated component is simply a dust map flipped north-south in Galactic coordinates. The spectral index of the free-free emission is assumed to be  $\beta = -0.16$  and the normalisation is that suggested by Bouchet & Gispert (1999).

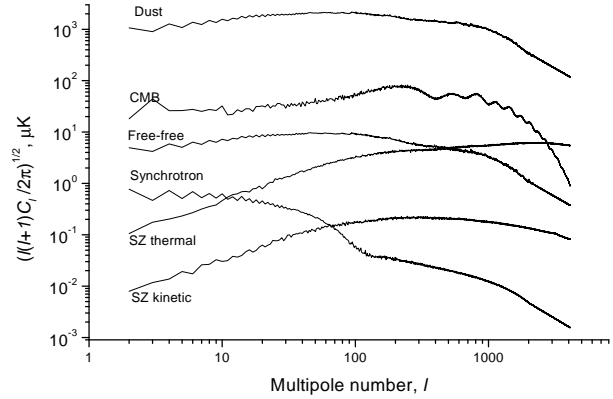
## 3 SIMULATED PLANCK OBSERVATIONS

If we observe the sky at  $n_f$  observing frequencies then, in any given direction  $\hat{x}$ , we obtain a *data vector* of length  $n_f$  that contains the observed temperature fluctuation in this direction at each observing frequency plus instrumental noise. In order to relate this data vector to the emission from each physical component it is useful to introduce the  $n_f \times n_c$  *frequency response matrix* with components defined by

$$F_{\nu p} = \int_0^\infty t_\nu(\nu') f_p(\nu') d\nu',$$

<sup>2</sup> <http://www.swarthmore.edu/Home/News/Astronomy/>

<sup>3</sup> <http://www.astro.wisc.edu/wham/>



**Figure 2.** Power spectra of the input maps shown in Fig. 1

where  $t_\nu(\nu')$  is the frequency response (or transmission) of the  $\nu$ th frequency channel. Assuming that the satellite observing beam in each channel is spatially-invariant, we may write the beam-smoothing as a convolution and the  $\nu$ th component of the data vector in the direction  $\hat{x}$  is then given by

$$d_\nu(\hat{x}) = \int_{4\pi} B_\nu(\hat{x} \cdot \hat{x}') \sum_{p=1}^{n_c} F_{\nu p} s_p(\hat{x}') d\Omega' + \epsilon_\nu(\hat{x}) \quad (2)$$

where  $B_\nu$  is the beam profile for the  $\nu$ th frequency channel. The beam profile at each frequency is assumed to be Gaussian. The  $\epsilon_\nu(\hat{x})$  term represents the instrumental noise on the observations in the  $\nu$ th channel, which for simplicity we assume to be uncorrelated Gaussian noise with a fixed rms over the whole sky. The assumed observational parameters of the Planck satellite are given in Table 1. Fig. 3 shows the rms equivalent thermodynamic temperature fluctuation at each Planck frequency due to each physical component, in the sky region lying between Galactic latitudes  $65^\circ < b < 75^\circ$ . The rms instrumental noise per pixel in each frequency channel is also plotted.

If the beam profile at each frequency is spatially-invariant and circularly-symmetric, it is convenient to work in terms of spherical harmonic coefficients. We now consider the statistical properties of these coefficients.

### 3.1 All-sky observations

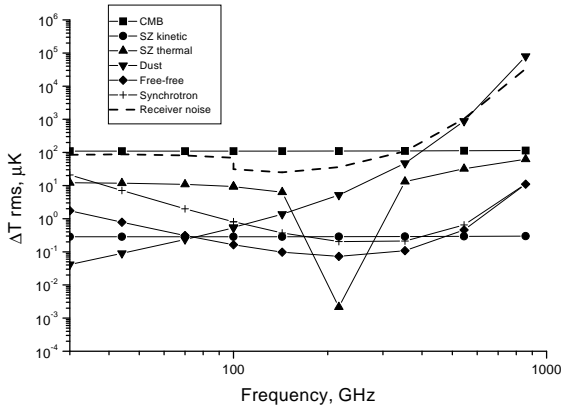
If each data map  $d_\nu(\hat{x})$  is defined over the whole sky, then on performing a spherical harmonic transform the convolution in (2) becomes a simple multiplication. Thus, we obtain

$$d_{\ell m}^{(\nu)} = \sum_{p=1}^{n_c} R_\ell^{(\nu p)} a_{\ell m}^{(p)} + \epsilon_{\ell m}^{(\nu)}, \quad (3)$$

where we have adopted the usual notation for spherical harmonic coefficients  $f_{\ell m} = \int_{4\pi} d\Omega Y_{\ell m}^*(\hat{x}) f(\hat{x})$  in which  $Y_{\ell m}(\hat{x})$  is a standard spherical harmonic function. Thus,  $d_{\ell m}^{(\nu)}$  are the spherical harmonic coefficients of the  $\nu$ th frequency map. These are related to the spherical harmonic coefficients

**Table 1.** The assumed observational parameters for the Planck Surveyor satellite. Angular resolution is quoted as FWHM for a Gaussian beam. Sensitivities are quoted per beam FWHM for 12 months of observation.

	Low Frequency Instrument				High Frequency Instrument					
Central frequency (GHz):	30	44	70	100	100	143	217	353	545	857
Fractional bandwidth ( $\Delta\nu/\nu$ ):	0.2	0.2	0.2	0.2	0.37	0.37	0.37	0.37	0.37	0.37
Transmission:	1.0	1.0	1.0	1.0	0.3	0.3	0.3	0.3	0.3	0.3
Angular resolution (arcmin):	33	23	14	10	10.6	7.4	4.9	4.5	4.5	4.5
$\Delta T$ sensitivity ( $\mu K$ ):	4.4	6.5	9.8	11.7	4.9	5.7	12.5	40.9	392	12621



**Figure 3.** The rms equivalent thermodynamic temperature fluctuation per pixel at each Planck observing frequency in the region of sky with Galactic latitude  $65^\circ < b < 75^\circ$ . The rms instrumental noise per pixel in each frequency channel is also plotted. The pixel size is 1.7 arcmin.

$a_{\ell m}^{(p)}$  of the  $p$ th physical component via the *response matrix* for the observations  $R_\ell^{(\nu p)} = B_\ell^{(\nu)} F_{\nu p}$ , where  $B_\ell^{(\nu)}$  are the harmonic coefficients of the  $\nu$ th observing beam. Finally,  $\epsilon_{\ell m}^{(\nu)}$  is the instrumental noise on the harmonic mode  $(\ell, m)$ . It is important to note that (3) is satisfied at each spherical harmonic mode  $(\ell, m)$  *independently*. Thus, in matrix notation, at each mode we have

$$\mathbf{d}_{\ell m} = \mathbf{R}_\ell \mathbf{a}_{\ell m} + \boldsymbol{\epsilon}_{\ell m}, \quad (4)$$

where  $\mathbf{d}_{\ell m}$ ,  $\mathbf{a}_{\ell m}$  and  $\boldsymbol{\epsilon}_{\ell m}$  are column vectors containing  $n_f$ ,  $n_c$  and  $n_f$  complex components respectively, and the response matrix  $\mathbf{R}_\ell$  has dimensions  $n_f \times n_c$ .

Although the data at a given  $(\ell, m)$  mode do not depend on the harmonics of the physical components at other modes, the a priori covariance structures of the harmonic coefficients of the components  $a_{\ell m}^{(p)}$  and the instrumental noise  $\epsilon_{\ell m}^{(\nu)}$  do correlate different modes. The sky emission (from the Galactic components) is anisotropic owing to the presence of pronounced emission from the Galactic plane. Furthermore, scanning strategies with non-uniform coverage of the sky lead to spatial variations in the noise rms per pixel, and so the instrumental noise field is also anisotropic. This results in a priori correlations between different  $(\ell, m)$  modes, so that in general we have

$$\langle \mathbf{a}_{\ell m} \mathbf{a}_{\ell' m'}^\dagger \rangle = \mathbf{C}_{\ell m, \ell' m'}, \quad (5)$$

$$\langle \boldsymbol{\epsilon}_{\ell m} \boldsymbol{\epsilon}_{\ell' m'}^\dagger \rangle = \mathbf{N}_{\ell m, \ell' m'}, \quad (6)$$

where we have defined the set of ensemble-average signal and noise covariance matrices  $\mathbf{C}_{\ell m, \ell' m'}$  and  $\mathbf{N}_{\ell m, \ell' m'}$ . Each matrix  $\mathbf{C}_{\ell m, \ell' m'}$  has dimensions  $n_c \times n_c$  and contains the a priori covariances of the harmonic coefficients of the different physical components at the modes  $(\ell, m)$  and  $(\ell', m')$ . Each matrix  $\mathbf{N}_{\ell m, \ell' m'}$  has dimensions  $n_f \times n_f$  and contains the covariances between the modes of the instrumental noise harmonics at the different observing frequencies. It should also be remembered that the emission from components other than the CMB is highly non-Gaussian and so these second-order statistics will not, in general, provide a full statistical description of the sky emission, particularly in the Galactic plane. In principle, we can also include any prior information about noise correlation properties in the noise covariance matrix  $\mathbf{N}$ . A typical example is non-homogeneous pixel noise in each frequency channel.

### 3.2 Galactic cuts

Since Planck is primarily a CMB instrument, ‘component separation’ is often taken to mean ‘foreground removal’. In particular, mapping of Galactic emission is regarded only as a secondary goal of the mission. When performing an all-sky foreground removal, one might therefore consider first removing the pronounced emission from the Galactic plane by imposing a Galactic cut on each individual frequency map. The new input data maps are then given by

$$\tilde{d}_\nu(\hat{\mathbf{x}}) = W(\hat{\mathbf{x}}) d_\nu(\hat{\mathbf{x}}), \quad (7)$$

where the window  $W(\hat{\mathbf{x}})$  is zero in the Galactic cut and equals unity outside it (although more general windows are possible). As indicated in (7), the window  $W$  is usually chosen to be the same for each observing frequency, and is often taken to be symmetric about the Galactic equator (for ease of computation, as discussed below). Indeed, this approach was adopted by Prunet et al. (2001).

The imposition of a Galactic cut does, however, produce some troublesome effects. Firstly, the spherical harmonic basis  $Y_{\ell m}(\hat{\mathbf{x}})$  is no longer orthonormal over the cut-sphere. For the Wiener filter approach, in particular, this leads to inconsistencies between performing the component separation in real space and harmonic space (see Prunet et al.). Secondly, the Galactic cut leads to additional correlations between harmonic coefficients at different  $(\ell, m)$  modes. For a function  $f(\hat{\mathbf{x}})$  defined on the sphere, the harmonic modes after the Galactic cut  $\tilde{f} = Wf$  are given by

$$\tilde{f}_{\ell m} = \int_{4\pi} d\Omega Y_{\ell m}^*(\hat{\mathbf{x}}) W(\hat{\mathbf{x}}) f(\hat{\mathbf{x}}) = \sum_{\ell', m'} W_{\ell m, \ell' m'} f_{\ell' m'},$$

where the coupling matrix is

$$W_{\ell m, \ell' m'} = \int_{4\pi} d\Omega W(\hat{\mathbf{x}}) Y_{\ell m}^*(\hat{\mathbf{x}}) Y_{\ell' m'}(\hat{\mathbf{x}}).$$

The problem of loss of orthonormality is usually solved by performing the entire analysis in terms of a new basis  $Y'_{\ell m}(\hat{\mathbf{x}})$  that is orthonormal on the cut-sky, such that

$$\int_{4\pi} d\Omega W(\hat{\mathbf{x}}) Y_{\ell m}^* Y'_{\ell' m'}(\hat{\mathbf{x}}) = \delta_{\ell\ell'} \delta_{mm'}.$$

For  $\ell_{\max} \lesssim 50$ , this basis can be constructed by performing a Cholesky decomposition of the coupling matrix (Gorski 1994). For higher  $\ell_{\max}$ , a singular value decomposition (SVD) is required (Tegmark 1997; Mortlock, Challinor & Hobson 2001). We note that, for simulated MAP data with  $\ell_{\max} = 512$ , Prunet et al. find the computational and memory costs of computing the new orthonormal basis to be reasonable, but the corresponding computing requirements for Planck will be somewhat larger. Perhaps more importantly, the computation of the new orthonormal basis is entirely unfeasible for either MAP or Planck unless the edges of the Galactic cut are chosen to be lines of constant latitude. It should also be remembered that for the new basis functions the subscripts  $\ell$  and  $m$  no longer have their usual physical meanings. Nevertheless, for large  $\ell_{\max}$  (such as for MAP or Planck) the new basis functions  $Y'_{\ell m}(\hat{\mathbf{x}})$  are very close to zero in the cut, and so the coefficients of these modes have the desirable property of being insensitive to emission from the cut region.

Unfortunately, the construction of the new orthonormal basis does not solve the problem of mode coupling. The new basis can be expressed as a linear combination of the standard spherical harmonic basis functions,

$$Y'_{\ell m}(\hat{\mathbf{x}}) = \sum_{\ell', m'} O_{\ell m, \ell' m'} Y_{\ell' m'}(\hat{\mathbf{x}}),$$

where matrix elements  $O_{\ell m, \ell' m'}$  are given by the ‘overlap’ integrals of the new and old basis functions,

$$O_{\ell m, \ell' m'} = \int_{4\pi} d\Omega Y_{\ell m}^*(\hat{\mathbf{x}}) Y_{\ell' m'}(\hat{\mathbf{x}}).$$

If we expand the sky emission from the physical components in terms of our new basis, we thus obtain

$$\mathbf{a}'_{\ell m} = \sum_{\ell', m'} O_{\ell m, \ell' m'} \mathbf{a}_{\ell' m'}, \quad (8)$$

and a similar expression holds for the coefficients  $\epsilon'_{\ell m}$  of the instrumental noise field at each observing frequency. Hence, the a priori correlation structure in the new basis is given by

$$\langle \mathbf{a}'_{\ell m} \mathbf{a}'_{\ell' m'}^\dagger \rangle = \mathbf{C}'_{\ell m, \ell' m'}, \quad (9)$$

$$\langle \epsilon'_{\ell m} \epsilon'_{\ell' m'}^\dagger \rangle = \mathbf{N}'_{\ell m, \ell' m'}, \quad (10)$$

where explicit expressions for  $\mathbf{C}'_{\ell m, \ell' m'}$  and  $\mathbf{N}'_{\ell m, \ell' m'}$  are easily obtained from (8), (5) and (6). In general, coupling still persists between different  $(\ell, m)$  modes.

An additional problematic feature of performing a Galactic cut is that the operation of beam convolution is no longer diagonal in the new orthonormal basis. From (3) and (8), we have

$$d'_{\ell m}^{(\nu)} = \sum_{p=1}^{n_c} \sum_{\ell' m'} R_{\ell' m'}^{(\nu p)} O_{\ell m, \ell' m'} a_{\ell' m'}^{(p)} + \epsilon'_{\ell m}^{(\nu)}, \quad (11)$$

which, in general, *cannot* be written in the form

$$\mathbf{d}'_{\ell m} = \mathbf{R}'_{\ell m} \mathbf{a}'_{\ell m} + \epsilon'_{\ell m}. \quad (12)$$

and this leads to further coupling between different  $(\ell, m)$  modes. Thus, in general, the operation of beam convolution is not merely non-diagonal, but is not strictly defined in a formal sense. We note, however, that we can write (11) in this form in the special case where the response matrix  $\mathbf{R}$  is not a function of  $\ell$ . This corresponds to no beam convolution.

### 3.3 Incomplete sky coverage

Similar considerations to the above also apply to incomplete sky coverage resulting from, for example, the scanning strategy of the satellite or instrument failure. In this case, however,  $W$  can be highly irregular in shape and different for each observing frequency. If the affected regions are not too large one could define a single window  $W$  that encompasses the unobserved regions at all frequencies, but this would probably not be viable in practice. Moreover, it is unlikely that one could find an adequate Galactic cut with edges at constant latitude, and so it would be computationally impossible to construct a new orthonormal basis on the cut-sky.

### 3.4 Choice of basis functions

Following the above discussion, we have the choice of performing the calculation in terms of the standard spherical harmonic basis functions  $Y_{\ell m}$  or some other basis  $Y'_{\ell m}$  that is orthonormal on the part of the sky outside some constant latitude Galactic cut. In both bases, there is coupling of modes through their a priori covariance structure, as defined by (5–6) or (9–10) respectively. Thus, in either case, a general analysis of the data cannot be performed ‘mode-by-mode’, but requires one to estimate the full ‘signal’ vector  $\mathbf{a}$  (or  $\mathbf{a}'$ ) simultaneously from the full data vector  $\mathbf{d}$  (or  $\mathbf{d}'$ ); these vectors can be regarded simply as the concatenation of the vectors  $\mathbf{a}_{\ell m}$  and  $\mathbf{d}_{\ell m}$  respectively for all possible values of  $\ell$  and  $m$  (or their primed counterparts).

It is also worth noting, however, that in the cut-sky basis one must *assume* that (12) holds, which is not valid unless there is no beam convolution. This assumption is, of course, unnecessary in the standard harmonic basis, since (4) holds exactly for all-sky observations. The assumption (12) will, in general, lead to reconstruction artefacts which are most pronounced near the edges of the Galactic cut.

Owing to the above difficulties of working in the cut-sky basis, and given that we are interested in recovering maps of the Galactic components as well as the CMB, in this paper we choose *not* to impose a Galactic cut, and instead attempt to reconstruct the physical components over the *whole sky*. Thus we perform our calculations in the standard spherical harmonic basis.

## 4 COMPONENT SEPARATION

The aim of any component separation algorithm is to use the data maps  $d_\nu(\hat{\mathbf{x}})$  at each frequency to obtain an estimated maps  $\hat{s}_p(\hat{\mathbf{x}})$  of the emission from each physical component. Typical methods include singular-valued decomposition, Wiener filtering or the maximum-entropy method, all of which can be viewed in Bayesian context (see Paper I).

### 4.1 Harmonic-space maximum-entropy method

A complete description of the ‘mode-by-mode’ Fourier-space MEM component separation algorithm as applied to small patches of sky is given in Paper I. The main difference in applying the technique to all-sky reconstructions is that Fourier transforms must be replaced by spherical harmonic transforms. Aside from this modification, the algorithm remains basically unchanged, and so we give only a brief outline here.

Let us consider the standard (unprimed) spherical harmonic basis, although the following discussion is equally valid for the primed basis described above. Using Bayes’ theorem, the estimator  $\hat{\mathbf{a}}$  of the signal vector is usually taken to be that which maximises the posterior probability

$$\Pr(\mathbf{a}|\mathbf{d}) \propto \Pr(\mathbf{d}|\mathbf{a}) \Pr(\mathbf{a})$$

where  $\Pr(\mathbf{d}|\mathbf{a})$  is the likelihood of obtaining the data given a particular signal vector and  $\Pr(\mathbf{a})$  is the prior probability that codifies our expectations about the signal vector before acquiring any data. Indeed, it is the specification of the prior alone that differentiates between different component separation algorithms such as singular-value decomposition, Wiener filtering and the maximum-entropy method (see Paper I).

Unfortunately, the lengths of the (complex) data and signal vectors are  $\sim n_f l_{\max}^2$  and  $\sim n_c l_{\max}^2$ , and so for MAP or Planck observations the dimensionality of the numerical maximisation problem renders it computationally unfeasible. It is therefore necessary to make some approximation. The most straightforward approximation is to neglect any coupling between different  $(\ell, m)$  modes, and perform the reconstruction independently ‘mode-by-mode’. Although this may appear an extreme approximation, we will see in Section 5 that it still produces excellent reconstructions. Taking the modes to be independent corresponds to assuming that the likelihood and prior probability distributions factorise, such that

$$\Pr(\mathbf{d}|\mathbf{a}) = \prod_{\ell, m} \Pr(\mathbf{d}_{\ell m}|\mathbf{a}_{\ell m}), \quad (13)$$

$$\Pr(\mathbf{a}) = \prod_{\ell, m} \Pr(\mathbf{a}_{\ell m}). \quad (14)$$

This offers an enormous computational advantage, since one can maximise the posterior probability

$$\Pr(\mathbf{a}_{\ell m}|\mathbf{d}_{\ell m}) \propto \Pr(\mathbf{d}_{\ell m}|\mathbf{a}_{\ell m}) \Pr(\mathbf{a}_{\ell m})$$

at each mode separately. Thus one replaces a single numerical maximisation over a parameter space with  $2n_c l_{\max}^2$  real dimensions by  $l_{\max}^2$  separate minimisations with  $2n_c$  real dimensions.

The factorisations (13) and (14) imply an assumed a

priori covariance structure of the form

$$\begin{aligned} \langle \mathbf{a}_{\ell m} \mathbf{a}_{\ell' m'}^\dagger \rangle &= \mathbf{C}_{\ell m} \delta_{\ell \ell'} \delta_{m m'}, \\ \langle \boldsymbol{\epsilon}_{\ell m} \boldsymbol{\epsilon}_{\ell' m'}^\dagger \rangle &= \mathbf{N}_{\ell m} \delta_{\ell \ell'} \delta_{m m'}. \end{aligned}$$

Although not required by the mathematical formalism, we have made the additional simplifying assumption that  $\mathbf{C}_{\ell m}$  and  $\mathbf{N}_{\ell m}$  do not depend on  $m$ , so that

$$\langle \mathbf{a}_{\ell m} \mathbf{a}_{\ell' m'}^\dagger \rangle = \mathbf{C}_\ell \delta_{\ell \ell'} \delta_{m m'}, \quad (15)$$

$$\langle \boldsymbol{\epsilon}_{\ell m} \boldsymbol{\epsilon}_{\ell' m'}^\dagger \rangle = \mathbf{N}_\ell \delta_{\ell \ell'} \delta_{m m'}. \quad (16)$$

In the standard spherical harmonic basis, this approximation is equivalent to assuming that the emission from each physical component and the instrumental noise are all isotropic random fields on the celestial sphere. The matrices  $\mathbf{C}_\ell$  and  $\mathbf{N}_\ell$  contain the (cross) power spectra of, respectively, the physical components at  $\nu_0$  and the instrumental noise at each observing frequency. Unfortunately, the analogous approximation in the cut-sky basis does not have such a straightforward interpretation.

At each  $(\ell, m)$  mode, any a priori correlation information is contained in the matrix  $\mathbf{C}_\ell$ . As explained in Paper I, this information is most easily incorporated into the reconstruction algorithm by first defining a ‘hidden’ vector  $\mathbf{h}_{\ell m}$  at each mode, that is related to the vector  $\mathbf{a}_{\ell m}$  by

$$\mathbf{a}_{\ell m} = \mathbf{L}_\ell \mathbf{h}_{\ell m}. \quad (17)$$

The  $n_c \times n_c$  lower triangular matrix  $\mathbf{L}_\ell$  is obtained by performing the Cholesky decomposition  $\mathbf{C}_\ell = \mathbf{L}_\ell \mathbf{L}_\ell^\dagger$ . The components of the hidden vector thus have the useful property of being a priori uncorrelated with unit variance, since then

$$\langle \mathbf{a}_{\ell m} \mathbf{a}_{\ell m}^\dagger \rangle = \langle \mathbf{L}_\ell \mathbf{h}_{\ell m} \mathbf{h}_{\ell m}^\dagger \mathbf{L}_\ell^\dagger \rangle = \mathbf{L}_\ell \langle \mathbf{h}_{\ell m} \mathbf{h}_{\ell m}^\dagger \rangle \mathbf{L}_\ell^\dagger = \mathbf{C}_\ell.$$

The reconstruction is then performed entirely in terms of  $\mathbf{h}_{\ell m}$  and the corresponding reconstructed signal vector is subsequently found using (17).

Assuming the instrumental noise to be Gaussian, the likelihood function at each mode is given by

$$\Pr(\mathbf{d}_{\ell m}|\mathbf{h}_{\ell m}) \propto \exp[-\chi^2(\mathbf{h}_{\ell m})],$$

where  $\chi^2$  is the standard misfit statistic given by

$$\chi^2(\mathbf{h}_{\ell m}) = (\mathbf{d}_{\ell m} - \mathbf{R}_\ell \mathbf{L}_\ell \mathbf{h}_{\ell m})^\dagger \mathbf{N}_\ell^{-1} (\mathbf{d}_{\ell m} - \mathbf{R}_\ell \mathbf{L}_\ell \mathbf{h}_{\ell m})$$

For the prior  $\Pr(\mathbf{h}_{\ell m})$ , we assume the entropic form

$$\Pr(\mathbf{h}_{\ell m}) \propto \exp[\alpha S(\mathbf{h}_{\ell m}, \mathbf{m})]$$

where  $S(\mathbf{h}_{\ell m}, \mathbf{m})$  is the cross entropy of the complex vectors  $\mathbf{h}_{\ell m}$  and  $\mathbf{m}$ , where  $\mathbf{m}$  is a model vector to which  $\mathbf{h}_{\ell m}$  defaults in absence of data. The form of the cross entropy for complex images is given in Paper I. Thus, maximising the posterior probability  $\Pr(\mathbf{h}_{\ell m}|\mathbf{d}_{\ell m})$  with respect to  $\mathbf{h}_{\ell m}$  is equivalent to minimising the function

$$\Phi(\mathbf{h}_{\ell m}) = \chi^2(\mathbf{h}_{\ell m}) - \alpha S(\mathbf{h}_{\ell m}, \mathbf{m}). \quad (18)$$

As explained in Paper I, the regularising parameter  $\alpha$  can be determined in a Bayesian manner by treating it simply as another parameter in the hypothesis space. Indeed, by assuming a Gaussian form for the posterior probability distribution near its maximum, one can derive a closed-form expression for the optimal value of  $\alpha$  (see Paper I). Since the calculation is performed at each  $(\ell, m)$  mode independently,

one could in principle obtain the optimal value of  $\alpha$  separately for each mode. However, since the dimensionality of the parameter space at each mode is only  $2n_c$ -dimensional (i.e. 12-dimensional in our case), the Gaussian approximation to the posterior distribution is occasionally too inaccurate to determine  $\alpha$  properly. Nevertheless, we would not expect the optimal level of regularisation to depend strongly on  $m$ , but to vary considerably with  $\ell$ . Thus we assume the optimal value of  $\alpha$  to be the same for all modes at the same  $\ell$ . Taking these modes together, the dimensionality of the parameter space is then sufficiently large that the Gaussian approximation to the posterior distribution is reasonably accurate, and the optimal value of  $\alpha$  is well-determined. Thus, the harmonic-space MEM algorithm employs optimal, scale-dependent regularisation, which allows for a more accurate reconstruction.

The numerical minimisation of (18) can be performed using a variable metric minimiser (Press et al. 1994). As a result of the independence of each  $(\ell, m)$  mode, parallelisation of the separation algorithm is straightforward. Full-resolution Planck simulations in HEALPIX with  $N_{\text{side}} = 2048$  have a maximum multipole  $\ell_{\text{max}} = 3N_{\text{side}} - 1 = 6143$ . The entire component separation can be performed in  $\sim 6$  hr using 30 R10000 processors on the ‘COSMOS’ SGI Origin 2000 supercomputer and required only 14 Gb of RAM.

As shown in Paper I, one can also estimate the covariance matrix of the reconstruction errors on the harmonic modes  $\mathbf{a}_{\ell m}$ . Making a Gaussian approximation to the posterior distribution at each mode, we find

$$\langle (\hat{\mathbf{a}}_{\ell m} - \mathbf{a}_{\ell m})(\hat{\mathbf{a}}_{\ell m} - \mathbf{a}_{\ell m})^\dagger \rangle = \mathbf{L}_\ell \mathbf{H}_{\ell m}^{-1} \mathbf{L}_\ell^\dagger, \quad (19)$$

where  $\mathbf{H}_{\ell m} = \nabla \nabla \Phi(\mathbf{h}_{\ell m})$  is the Hessian matrix of the posterior distribution at its peak  $\mathbf{h}_{\ell m}$ . For full-resolution Planck data, the calculation of the errors on the component separation required just 15 mins additional computation time on COSMOS.

## 5 APPLICATION TO SIMULATED DATA

We now apply the separation algorithm outlined above to the simulated Planck Surveyor observations described in Section 3. Owing to the limited resolution of our foreground maps, we only consider multipoles up to  $\ell_{\text{max}} = 4096$ , which is the Nyquist sampling limit for pixels of size 1.7 arcmin. This reduces both the computation time and memory required by about a factor of two, as compared with the case  $\ell_{\text{max}} = 6143$ .

Clearly, the quality of the reconstructions will depend on our prior knowledge of the input components. Following Paper I, we assume that the frequency spectrum behaviour of the components is accurately known. Nevertheless, as mentioned in the introduction, the relaxation of this assumption has been investigated by Jones et al. (1999), who showed that it is possible to accommodate mild uncertainties in frequency behaviour and spatial variation of spectral indices. Prior power information may be incorporated into the algorithm through the signal covariance matrix  $\mathbf{C}_\ell$  given in (15). Similarly, any knowledge of the correlation structure of the instrumental noise can be included via the noise covariance matrix  $\mathbf{N}_\ell$ . In our simulated data, however, we assume homo-

geneous, uncorrelated instrumental noise in each frequency channel.

### 5.1 Partial prior covariance information

As an illustration, we begin by assuming knowledge of the azimuthally-averaged power spectra of each input components, as shown in Fig. 2, *except* that of the CMB. Since the accurate determination of the positions and heights of the acoustic peaks in the CMB spectrum is of such fundamental importance, we choose not to prejudice our reconstruction by supplying the component separation algorithm with the power spectrum of the input CMB map. Thus, as our assumed CMB power spectrum, we take a simple functional form which matches the overall shape of the true spectrum, but contains no acoustic peaks (this assumed power spectrum is plotted as the dotted line in the first panel of Fig. 8).

The inclusion of the azimuthally-averaged input power spectra for the remaining components is reasonable, and would be possible in practice. As discussed in section 2, the maps of the kinetic and thermal SZ effect have been produced with some care, and we would expect them to provide a reasonably accurate representation of the true power spectra for these two components. Alternatively, one could use an average power spectrum for each SZ component obtained from a large number of simulated realisations, which would be statistically more accurate. For the Galactic components, the dust and synchrotron maps are simply taken from existing observations (albeit with some added structure on small scales). Unfortunately, considerable uncertainty remains for Galactic emission in the free-free. Nevertheless, free-free observations should be available before the Planck data are analysed, so that an approximate free-free power spectrum could be calculated. As discussed in section 2, for the time being, we create a free-free template based on the DIRBE/IRAS dust map, of which 60 per cent of the emission is a dust-correlated component and 40 per cent is uncorrelated, with the uncorrelated component being simply the dust map flipped north-south in Galactic coordinates.

We note, however, that, since we are assuming knowledge of only the power spectra of each component, the component separation algorithm has no a priori information concerning cross correlations between any of the components. In practice, a significant amount of cross correlation information should be available to the Planck mission from earlier observations, and so our assumed level of prior knowledge is, in this respect, mildly pessimistic.

#### 5.1.1 Reconstructed and residuals maps

The component separation algorithm produces an estimate  $\hat{\mathbf{a}}_{\ell m}$  of the harmonic coefficients of the physical components at each mode. Let  $a_{\ell m}^{(p)}$  be the true harmonic coefficient of the  $p$ th physical component at the mode  $(\ell, m)$ . This coefficient can be written

$$a_{\ell m}^{(p)} = \hat{a}_{\ell m}^{(p)} + \delta a_{\ell m}^{(p)}, \quad (20)$$

where  $\hat{a}_{\ell m}^{(p)}$  is the estimate of the mode obtained from the component separation algorithm and  $\delta a_{\ell m}^{(p)}$  is the residual on this mode. The reconstructed map of the  $p$ th physical

component is given simply by performing an inverse spherical harmonic transform on the reconstructed coefficients  $\hat{a}_{\ell m}^{(p)}$  using the HEALPIX package. It is also of interest to construct a map of the reconstruction residuals for each physical component. This can be calculated in two equivalent ways. One can either simply subtract the reconstructed map from the true input map, or one can perform an inverse spherical harmonic transform of the residuals  $\delta a_{\ell m}^{(p)}$ . We have verified that these two methods lead to residuals maps that are consistent to within the machine precision.

In Fig.4, we plot the reconstructions and residuals of the extragalactic components, namely the CMB and the kinetic and thermal SZ effects. We see that the CMB reconstruction is a faithful representation of the input map shown in Fig. 1. This is confirmed by the CMB residuals map, which contains very little structure. Indeed, only a thin band of residual emission remains in the CMB reconstruction in the very centre of the Galactic plane. Thus, the CMB map has been faithfully recovered over the whole sky, *without* the need to perform a Galactic cut prior to the component separation. It is also worth noting that the true input CMB map was *not* smoothed before calculating the reconstruction residuals. Fig.5 shows the distribution of pixel values in the residuals map. This distribution is well approximated by a Gaussian centred on zero with an rms of 12.3  $\mu$ K, except for low-level wings corresponding to the very few pixels in the Galactic plane that contain residual Galactic contamination.

In the absence of a priori cross-correlation information, we see that the recovery of the kinetic SZ effect is very poor, confirming the findings of Paper I. This result is not surprising, since the kinetic SZ effect has the same frequency spectrum as the primordial CMB but, as shown in Figs 2 and 3, its rms signal is 3 orders of magnitude smaller than the CMB component. However, the thermal SZ effect has been successfully recovered, particularly in the brighter clusters. The numbers of clusters recovered and accuracy achieved, together with the resulting cosmological information that could be obtained, will be discussed in detail in a forthcoming paper.

In Fig.6, we plot the reconstructions and residuals of the Galactic components, namely dust, free-free and synchrotron emission. Once again we see that each component has been successfully recovered over an extremely wide dynamic range in pixel values. In particular, the presence of strong emission from the Galactic plane clearly invalidates the assumption of uncorrelated harmonic modes, as discussed in section 4. Nevertheless, this approximation does not appear to have had a dramatic effect on the quality of the reconstructions. The accuracy of the reconstructions is confirmed by the corresponding residuals maps, which are mostly featureless apart from some slight residual emission in the central Galactic plane. The histograms of the pixel values in these residual maps are shown in Fig. 7. As for the CMB, each histogram is well approximated by a Gaussian centred on zero, except for low-level wings corresponding to the few pixels in the Galactic plane that contain residual contamination from other components. The parameters of the best-fit Gaussian to each of the residuals histograms in Figs 5 & 7 are given in Table 2. We note that the low values of  $\sigma$  for the kinetic SZ effect and Galactic synchrotron emission do not indicate that they are the most accurately

**Table 2.** The mean  $\mu$  and standard deviation  $\sigma$  (in  $\mu$ K) of the best-fit Gaussian to each of the residuals histograms shown in Figs 5 & 7.

Component	$\mu$	$\sigma$
CMB	0.11	12.30
Kinetic SZ	0.02	0.12
Thermal SZ	0.62	4.30
Dust	0.14	16.70
Free-Free	0.08	2.40
Synchrotron	$3 \times 10^{-4}$	0.11

reconstructed, but simply that the level of emission in these two components is very low at 300 GHz.

### 5.1.2 Power spectra of reconstructed and residuals maps

In the left-hand columns of Figs 8 & 9, we plot the power spectrum of the reconstructed map for each physical component (dotted line), together with the power spectrum of the true input map (solid line). For the  $p$ th physical component, the power spectrum of the reconstructed map is given simply by

$$\hat{C}_\ell^{(p)} \equiv \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |\hat{a}_{\ell m}^{(p)}|^2, \quad (21)$$

In the right-hand column of Figs 8 & 9, we plot the power spectrum of the residuals map for each component (solid line), which is given by

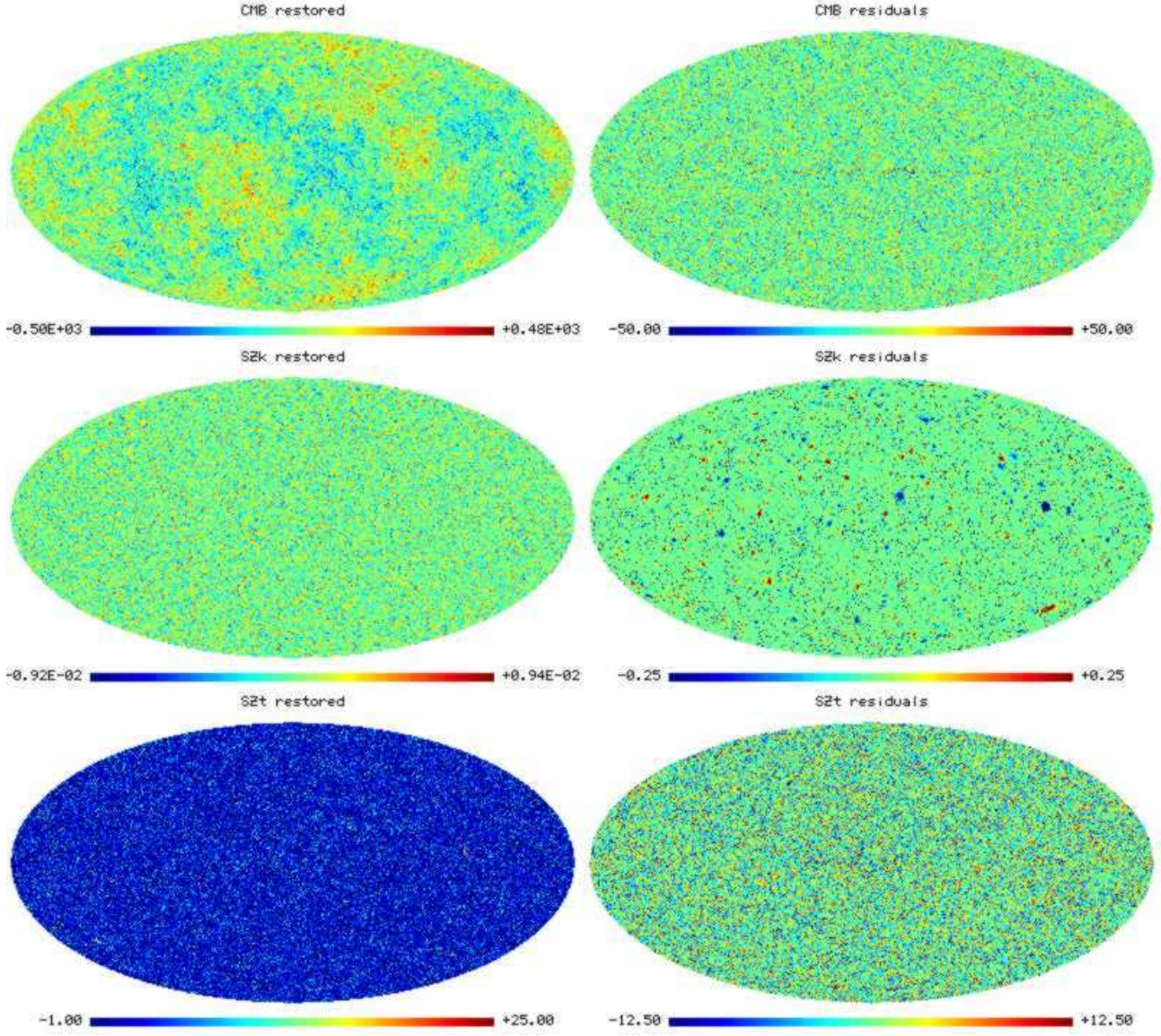
$$\delta C_\ell^{(p)} \equiv \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |\delta a_{\ell m}^{(p)}|^2. \quad (22)$$

Of course, in practice the true residuals  $\delta a_{\ell m}$  would not be available. Nevertheless, we can estimate the residuals power spectrum by calculating the Hessian matrix  $\mathbf{H}_{\ell m}$  of the posterior distribution at its peak. As discussed in section 4, this provides an estimate of the standard error on the reconstructed harmonic modes. From (19), we see that for the  $p$ th physical component  $|\Delta a_{\ell m}^{(p)}|^2 \equiv \langle |\delta a_{\ell m}^{(p)}|^2 \rangle$  is given by the  $p$ th diagonal entry of the matrix  $\mathbf{L}_\ell \mathbf{H}_{\ell m}^{-1} \mathbf{L}_\ell^\dagger$ . Thus, our estimator of the residuals power spectrum is simply

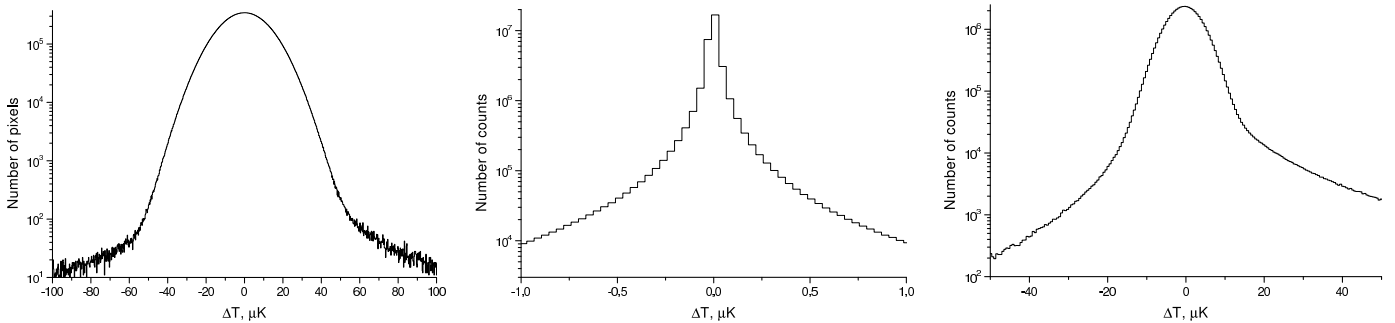
$$\widehat{\delta C}_\ell^{(p)} = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |\Delta a_{\ell m}^{(p)}|^2, \quad (23)$$

which is unbiased in the sense that  $\widehat{\delta C}_\ell^{(p)} = \langle \delta C_\ell^{(p)} \rangle$ , where the averages are over realisations of the instrumental noise and maps of the physical components. The estimated residuals power spectrum for each component is plotted as the dotted line in the right-hand columns of Figs 8 & 9.

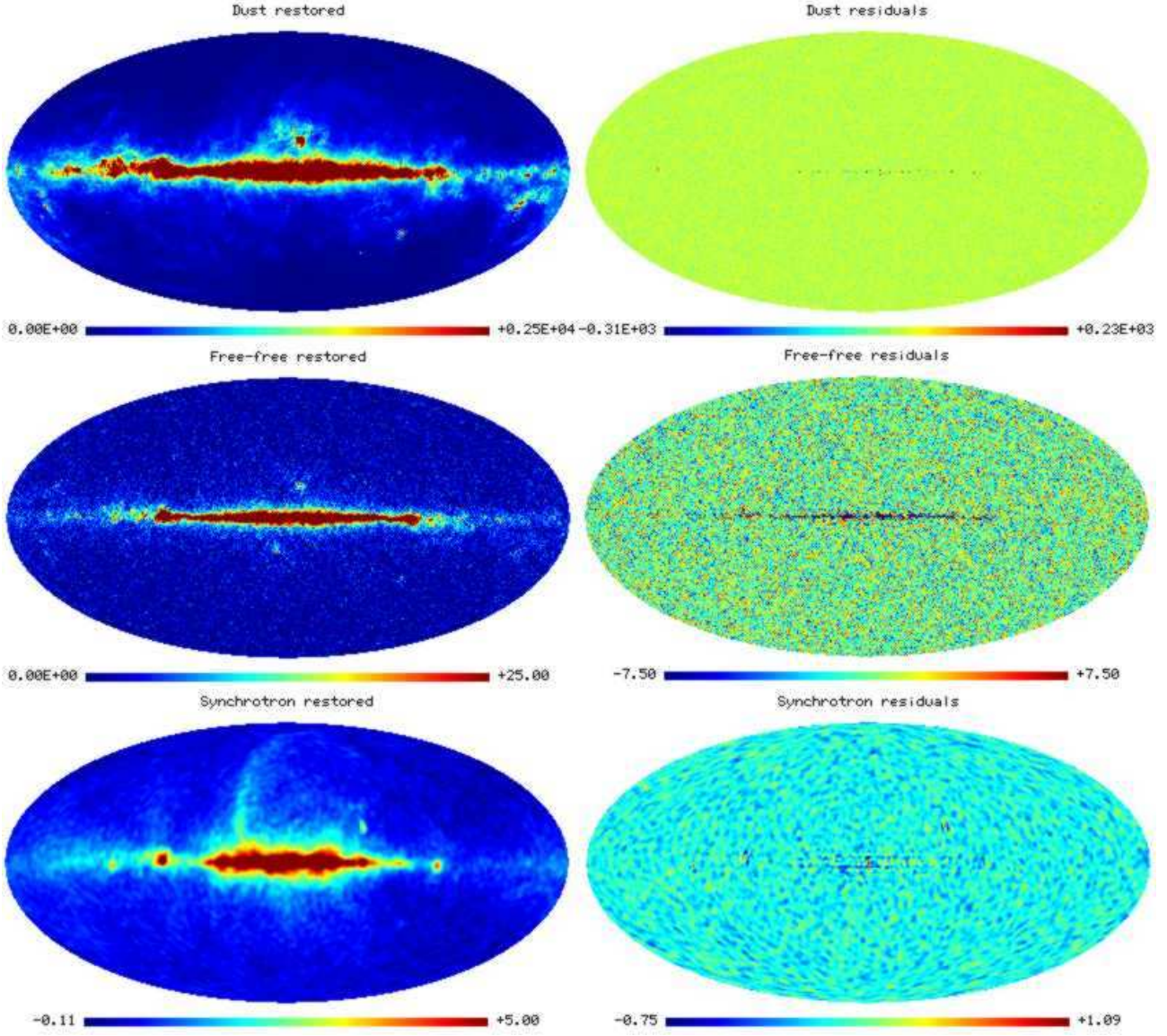
Fig. 8 shows the power spectra for the extragalactic components, namely the CMB and kinetic and thermal SZ effects. For the CMB, in addition to the power spectra of the input and reconstructed maps, we also plot the simple a priori form of the power spectrum assumed by the component separation algorithm. This assumed power spectrum contains no acoustic peak structure, so as not to prejudice the reconstruction. We see, however, that the power



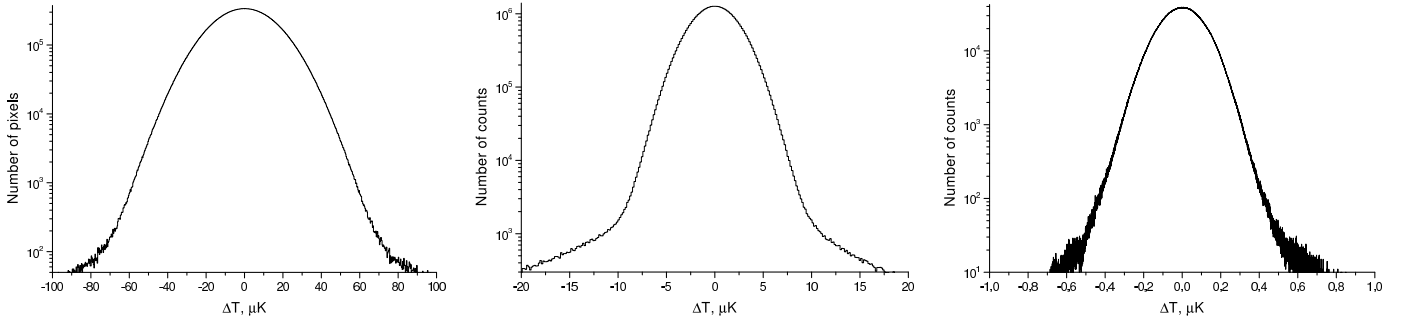
**Figure 4.** Reconstructions of the extragalactic components, namely the primordial CMB, the kinetic SZ effect and the thermal SZ effect (left-hand column). Also plotted are maps of the corresponding reconstruction residuals for each component (right-hand column). All maps are plotted in units of  $\mu\text{K}$ .



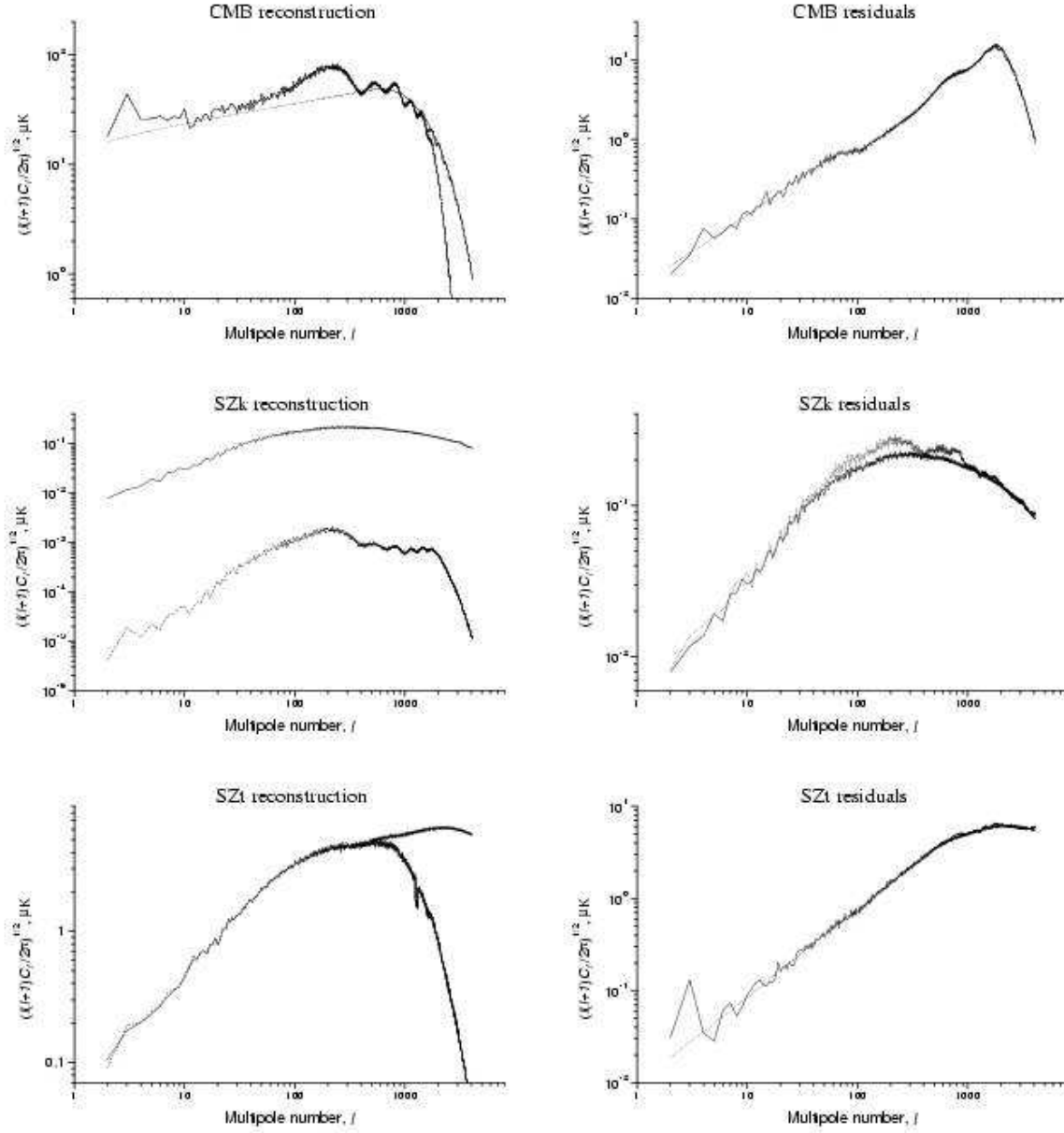
**Figure 5.** Histograms of the residuals maps for primordial CMB (left), the kinetic SZ effect (centre) and the thermal SZ effect (right).



**Figure 6.** Reconstructions of the Galactic components, namely the dust, free-free and synchrotron emission (left-hand column). Also plotted are maps of the corresponding reconstruction residuals for each component (right-hand column).



**Figure 7.** Histograms of the residuals maps for emission from dust (left), free-free (centre) and synchrotron (right).

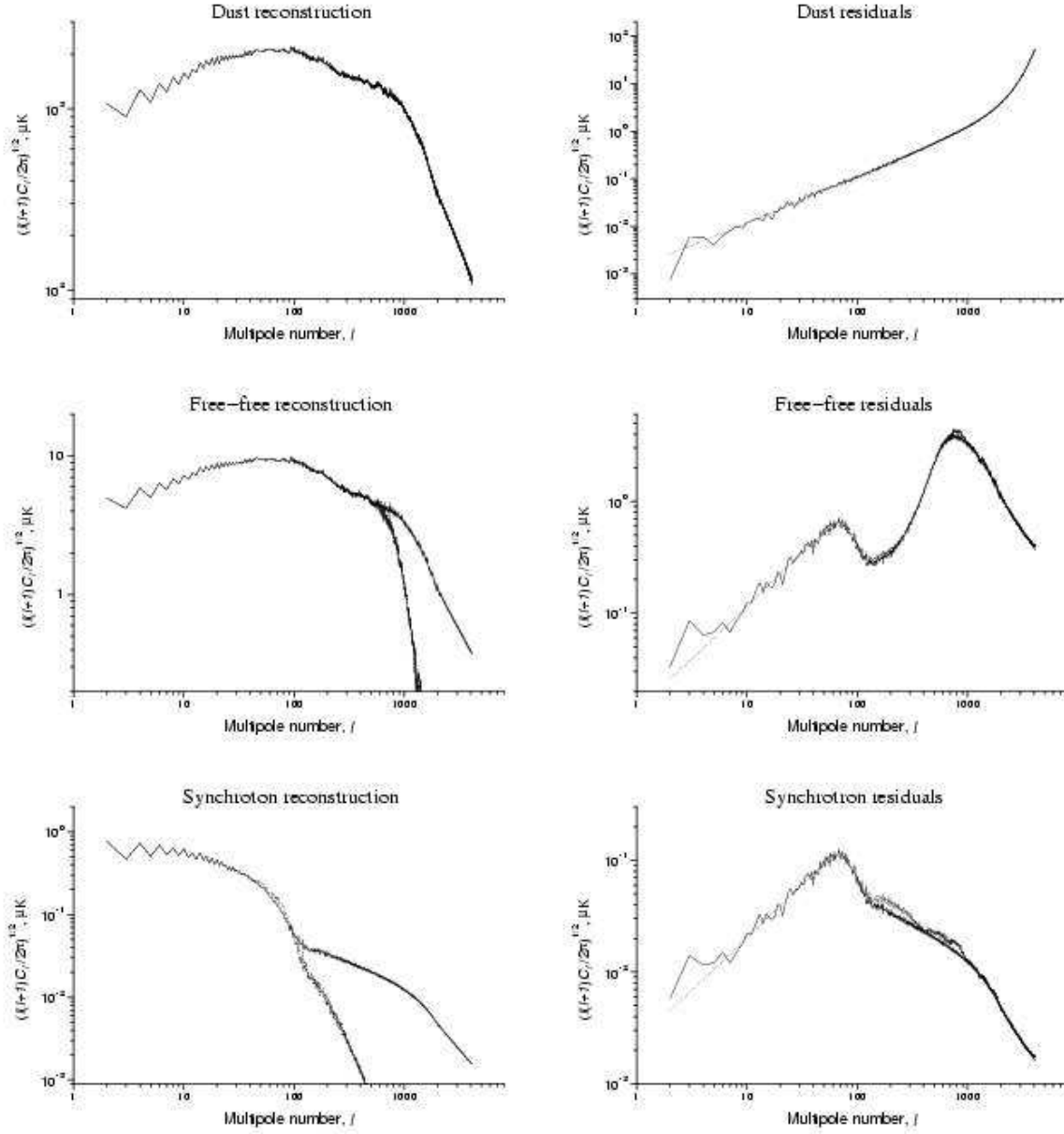


**Figure 8.** Power spectra of the reconstructed maps (dotted line) and input maps (solid line) of the extragalactic components, namely CMB, kinetic SZ and thermal SZ (left-hand column). The smooth dotted line in the CMB panel is the assumed input CMB power spectrum supplied to the algorithm. Also plotted are the power spectra of the residuals maps (solid line) and the predicted residuals power spectra (dotted line) for each component (right-hand column).

spectrum of the reconstructed map matches that of the input map up to  $\ell \approx 2000$ . In particular, the first 5 acoustic peaks have been accurately recovered, and there is some evidence of the presence of a 6th peak in the recovered power spectrum, although the amplitude is significantly underestimated. Indeed, beyond  $\ell \approx 2000$ , the power spectrum of the reconstructed map consistently underestimates that of the true map. This effect is due to the fact that (21) is a biased estimator of the true power spectrum. Nevertheless, as discussed below, we can easily construct an unbiased estimator. From Fig. 8, however, we see that our estimator for

the power spectrum of the CMB residuals is already unbiased, as we expected. Thus the MEM algorithm provides a good estimate of the statistics of the reconstruction errors.

The power spectra of the reconstructed kinetic SZ map severely underestimates the true power spectrum, as we might have expected. Indeed, one can see that the ‘recovered’ kinetic SZ map has a power spectrum which clearly mirrors that of the CMB, which suggests that any structure present in the kinetic SZ ‘reconstruction’ is dominated by contamination by primordial CMB. Nevertheless, once again the estimated residuals power spectrum is a good approxi-



**Figure 9.** As in Fig. 8, but for the Galactic components dust, free-free and synchrotron.

mation to the power spectrum of the true residuals map. In practice this would provide a robust indication of the poor quality of the kinetic SZ reconstruction.

For the thermal SZ effect, the power spectrum of the reconstructed map matches that of the input map up to  $\ell \approx 1000$ , beyond which the true spectrum is underestimated. This is again a result of (21) being a biased estimator. We see, however, that the predicted and actual residuals power spectra are in close agreement for all  $\ell$  values.

The power spectra of the reconstructed maps and residuals of the Galactic components are shown in Fig. 9. Qualitatively, we see similar behaviour to the observed for the extragalactic components, with the exception that the power spectrum of the input dust map is accurately recovered for

all  $\ell$ . For the free-free and synchrotron components, the underestimation of the true power spectrum is again due to the fact that (21) is a biased estimator. In each case, we again note that the estimated and actual residuals power spectrum agree well. The accuracy of this error estimation enables one to define an unbiased estimator of the true input power spectrum.

### 5.1.3 An unbiased power spectrum estimator

We see from the left-hand columns of Figs 8 & 9, that the power spectra of the reconstructed maps generally underestimate the true input power spectra at large  $\ell$ . Indeed, it is

easy to show that the estimator (21) is biased. From (20), we have  $\hat{a}_{\ell m}^{(p)} = a_{\ell m}^{(p)} - \delta a_{\ell m}^{(p)}$ , and on inserting this expression into (21), we see that the expectation value of this estimator is given by

$$\langle \hat{C}_\ell^{(p)} \rangle = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} \langle |a_{\ell m}^{(p)}|^2 \rangle + \langle |\delta a_{\ell m}^{(p)}|^2 \rangle - 2\langle a_{\ell m}^{*(p)} \delta a_{\ell m}^{(p)} \rangle$$

where the ensemble average is again taken over realisations of the instrumental noise and of the physical components. Using (20) again, we can write

$$\langle a_{\ell m}^{*(p)} \delta a_{\ell m}^{(p)} \rangle = \langle \hat{a}_{\ell m}^{*(p)} \delta a_{\ell m}^{(p)} \rangle + \langle |\delta a_{\ell m}^{(p)}|^2 \rangle. \quad (24)$$

If we assume that the reconstruction errors on each mode are not correlated with the reconstructed values (which is reasonable given the featureless nature of the residuals maps), the first term on the right-hand side of (24) disappears, and so we obtain

$$\begin{aligned} \langle \hat{C}_\ell^{(p)} \rangle &= \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} \langle |a_{\ell m}^{(p)}|^2 \rangle - \langle |\delta a_{\ell m}^{(p)}|^2 \rangle, \\ &= \langle C_\ell^{(p)} \rangle - \langle \delta C_\ell^{(p)} \rangle, \\ &= \langle C_\ell^{(p)} \rangle \left( 1 - \frac{\langle \delta C_\ell^{(p)} \rangle}{\langle C_\ell^{(p)} \rangle} \right). \end{aligned} \quad (25)$$

Thus, (21) is a biased estimator, which underestimates the true power spectrum of the  $p$ th component on angular scales where the residuals are large.

By analogy with the approach developed by Bouchet & Gispert (1999) and Knox (1995), we denote the quantity in brackets in (25) as the *quality factor*  $Q_\ell^{(p)}$ . We see immediately that an unbiased estimator of the power spectrum is given by simply by

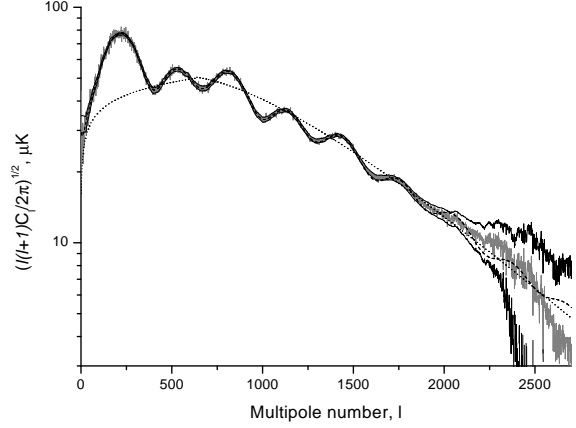
$$\hat{C}_\ell^{(p)} = \hat{C}_\ell^{(p)} \left( 1 - \frac{\widehat{\delta C}_\ell^{(p)}}{\langle C_\ell^{(p)} \rangle} \right)^{-1}, \quad (26)$$

where  $\widehat{\delta C}_\ell^{(p)}$  is given by (23). The variance of this estimator is given by

$$V[\hat{C}_\ell^{(p)}] = \frac{2}{2\ell+1} \left( \frac{\langle C_\ell^{(p)} \rangle}{Q_\ell^{(p)}} \right)^2. \quad (27)$$

which illustrates the uncertainty added by the foreground removal to cosmic variance.

As an illustration, in Fig. 10 we plot the unbiased estimator of the CMB power spectrum against the true power spectrum of the input map. We see from the plot that the estimated power spectrum is now fully consistent with the input power spectrum out to large  $\ell$  values. In particular, the heights and positions of the 5th and 6th acoustic peaks are now accurately recovered. Beyond the 6th peak, however, there is no evidence for further oscillatory structure in the power spectrum. At high  $\ell$ , the overall level of power is recovered correctly, but this is simply a result of our assumed power spectrum (the smooth dotted line in Fig. 10) having the appropriate normalisation in this region.



**Figure 10.** The power spectrum of the input CMB map (dashed line) compared with the unbiased estimator (26) of the power spectrum obtained from the CMB reconstruction (grey solid line). Also plotted are the 1- $\sigma$  error limits. The smooth dotted line shows the power spectrum of the CMB assumed as our prior in the component separation process.

**Table 3.** The mean  $\mu$  and standard deviation  $\sigma$  (in  $\mu\text{K}$ ) of the best-fit Gaussian to the residuals histograms for full a priori correlation information.

Component	$\mu$	$\sigma$
CMB	0.09	12.18
Kinetic SZ	0.02	0.09
Thermal SZ	0.60	4.50
Dust	0.14	16.70
Free-Free	0.05	1.58
Synchrotron	$5 \times 10^{-4}$	0.10

## 5.2 Full prior covariance information

As an indication of the best results one could reasonably expect, we now consider the case in which, in addition to the azimuthally-averaged power spectra of each input component, we also assume knowledge of the azimuthally-averaged cross power spectra between components. These provide some limited cross-correlation information between the components at each spherical harmonic mode. Moreover, in this case, we also provide the algorithm with the true power spectrum of the CMB input map, with its full acoustic peaks structure, rather than the simple functional form assumed above.

Most of the resulting reconstructed maps of components are found to be very similar to those obtained in the previous section, obtained using no cross-correlation information. We therefore do not reproduce them here in full, but list only the rms of the residuals maps in Table 3, which we see are very similar to those listed in Table 2.

In this section, we instead concentrate on the few qualitative differences in the reconstructions that occur due to the inclusion of cross-correlation information. The most striking difference occurs in the reconstruction of the kinetic SZ com-

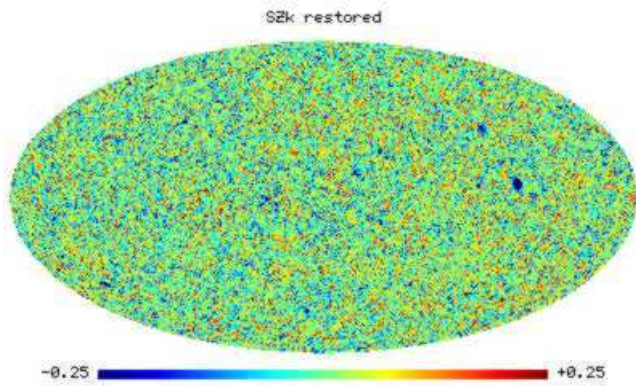


Figure 11. Reconstructed map of the kinetic SZ effect.

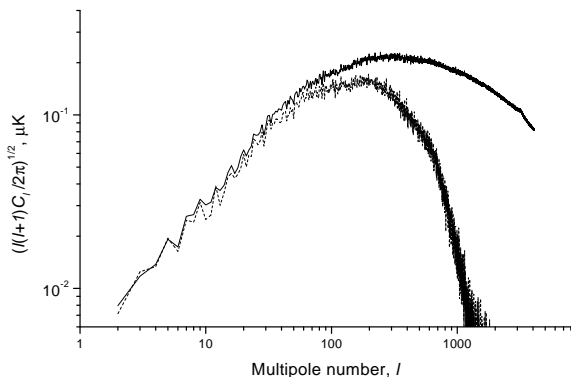


Figure 12. Power spectrum of reconstructed map of kinetic SZ effect (dotted line) compared to the power spectrum of the input map (solid line).

ponent. As shown in the previous section, in the absence of cross-correlation information, the kinetic SZ effect is essential not recovered at all. Indeed, from Fig. 8, we see that the low level emission in the kinetic SZ ‘reconstruction’ is residual contamination from the primordial CMB component. If some cross-correlation information is included, however, we see in Fig. 11, that the reconstruction of the kinetic SZ effect is recovered to reasonable accuracy only in those clusters possessing very large thermal SZ effects. This clearly shows that the incorporation of cross-correlation information between the two SZ effects enhances the kinetic SZ reconstruction. The improved quality of the reconstruction is also illustrated by its power spectrum, which is shown in Fig. 12 (together with the true power spectrum of the input map). We see that at least up to  $\ell \approx 100$ , the power in the reconstruction matches that of the input map. This is a significant improvement on the power spectrum of the reconstruction obtained using no cross-correlation information shown in Fig. 8.

The other major qualitative difference in the reconstruction concerns the recovery of the acoustic peaks in the CMB

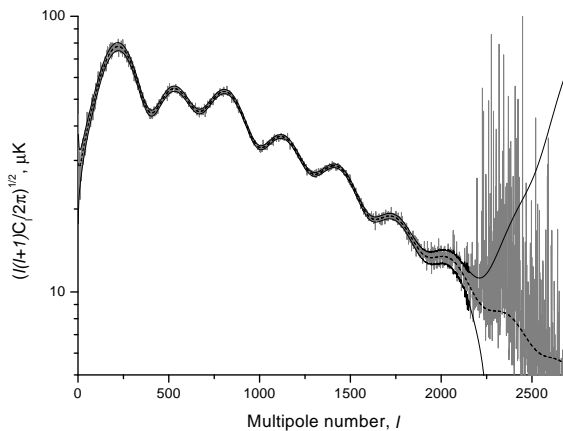


Figure 13. The power spectrum of the input CMB map (dashed line) compared with the unbiased estimator (26) of the power spectrum obtained from the CMB reconstruction (grey solid line). Also plotted are the  $1\text{-}\sigma$  error limits.

power spectrum. In Fig. 13 we plot the unbiased estimator (as discussed above) obtained from the reconstruction. We also plot the true power spectrum of the input CMB map and the  $1\text{-}\sigma$  error limits given by the square-root of the variance given in (27). To avoid inevitable scatter in the  $1\text{-}\sigma$  error limits at large  $\ell$ ,  $Q_\ell^{(p)}$  was approximated by the exponential function for  $\ell \geq 2200$ .

Comparing Figs 10 and 13, we observe qualitative differences at high- $\ell$ . Most importantly, we note that more of the acoustic peaks structure present in the true power spectrum is recovered. In particular, the 7th acoustic peak is now reproduced with its correct height and position. Beyond the 7th peak, however, error in our simple unbiased estimator becomes too large to discern any further detailed structure in the power spectrum. This result is in a good agreement with the analytical predictions by Bouchet & Gispert (1999) based on Wiener filtering of Gaussian foregrounds.

## 6 DISCUSSION

In this paper, we have performed an all-sky component separation over the whole sky for the Planck mission at full angular resolution. The technique employed is an harmonic-space maximum-entropy method, which performs a mode-by-mode reconstruction of the spherical harmonic coefficients of the component maps. Assuming knowledge only of the power spectra of the non-CMB components, the algorithm produces faithful reconstructions of the input maps, *without* the need to apply a Galactic cut. Indeed, it is the MEM prior that allows our component separation algorithm to cope with such a large dynamics range in pixel values. The only component not reconstructed is the kinetic SZ effect. We also assumed that the instrumental pixel noise is homogeneous and uncorrelated. However, non-homogeneous uncorrelated pixel noise can be easily included into the analysis. Preliminary investigations of simulations for more realistic Planck observing strategies suggest that the quality of

the reconstructions are not significantly reduced, provided one obtains reasonable sky coverage. A detailed analysis of the effects of scanning strategy on the accuracy of component separation will be presented in a forthcoming paper.

The power spectra of the reconstructions match those of the input maps (except for the kinetic SZ) on scales where the signal dominates the instrumental noise. At high  $\ell$  values, however, the power spectrum of the reconstruction consistently underestimates the power spectrum of the true map. Indeed, it is easily shown that this estimator is biased. Nevertheless, the component separation algorithm also produces an accurate predicted power spectra for the reconstruction residuals, which allows the construction of an unbiased power spectrum estimator. This accurately recovers the input power spectrum at all measured  $\ell$ .

The effect of including a priori cross-correlation information is also studied. The main effect is to improve somewhat the recovery of the kinetic SZ effect in clusters possessing a large thermal SZ effect. The assumed level of prior knowledge of the CMB power spectrum also affects the CMB reconstruction, but only at high  $\ell$ . In particular, we find that, if one assumes a CMB power spectrum with no acoustic peaks, the final reconstructed spectrum still recovers the oscillatory structure out to the 6th acoustic peak. If, however, the true CMB power spectrum is assumed in the component separation process, the recovered spectrum of the CMB contains the first 7 acoustic peaks with the correct heights and positions. It is also noted that some care must be taken in interpreting the recovered CMB power spectrum beyond  $\ell \approx 2000$ . In this region, the recovered spectrum is dominated by the assumed spectrum.

The simulations used in this paper did not contain a contribution from extragalactic point sources. As shown in Hobson et al. (1998), however, the MEM method can accommodate such components. Moreover, as discussed by Vielva et al. (2001), the MEM algorithm can be combined with a Mexican hat wavelet approach to detecting and removing point sources, which leads to a significant reduction in the residual point source contamination of the other physical components. Recently, Cayon et al. (2001) have presented a consistent method for defining the Mexican hat wavelet on a sphere, which can be combined with the algorithm presented here to separate out point source emission in all-sky maps. This will be discussed in detail in a forthcoming paper. In a future publication, we will also present a detailed statistical analysis of the recovery of the kinetic and thermal SZ effects in clusters, and discuss its cosmological implications.

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